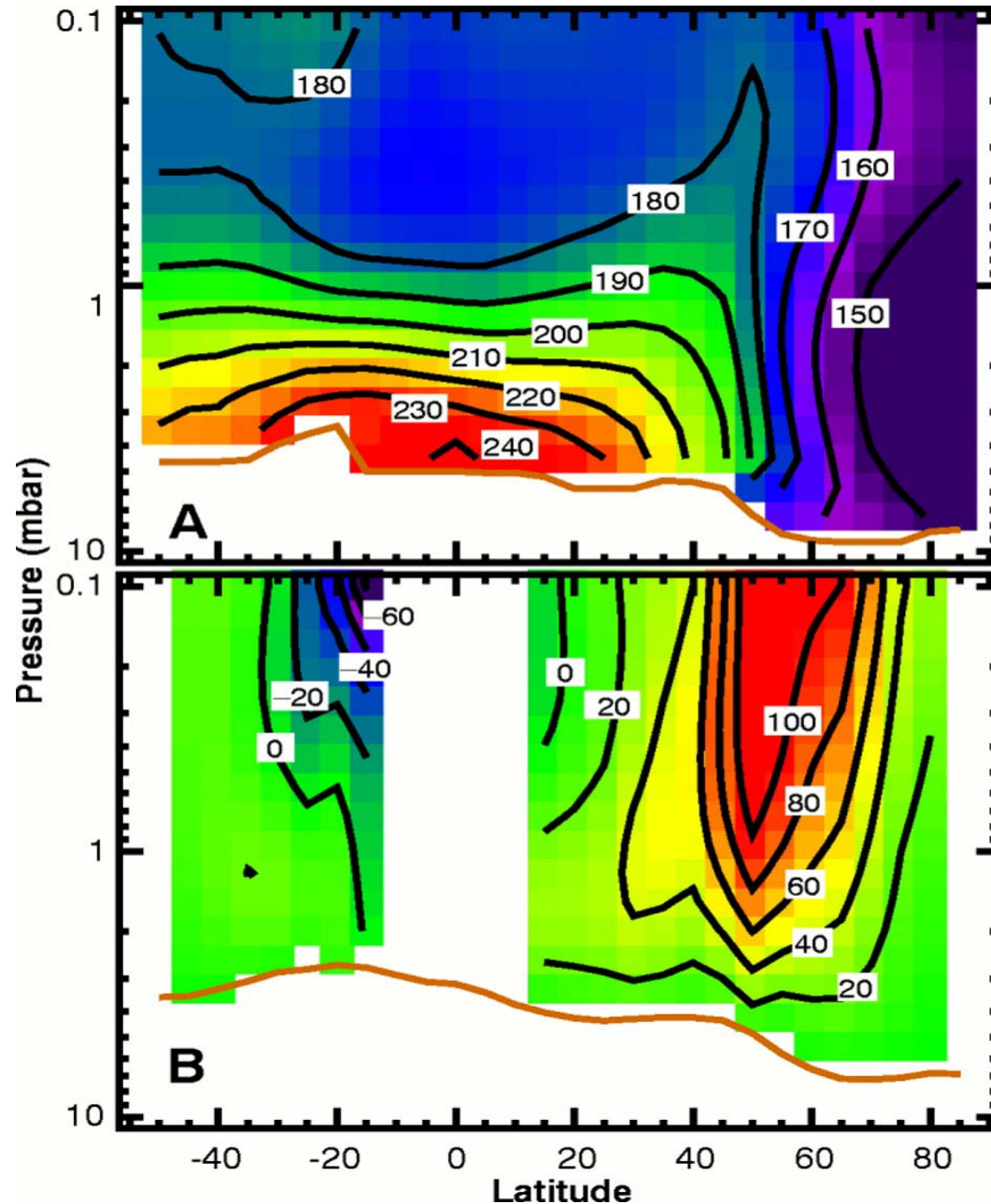


Atmospheric Environments for Entry, Descent and Landing (EDL)

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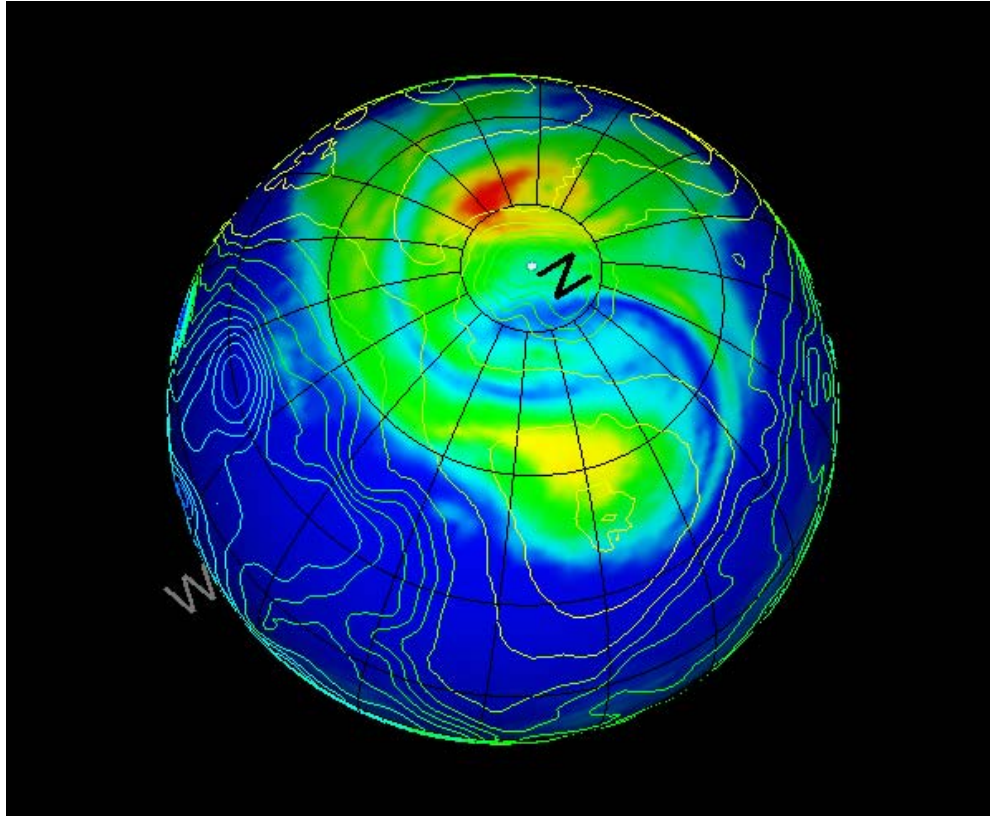
June, 2007

Atmospheric Data and Models for Science



- Most atmospheric remote sensing and science-application atmospheric models provide temperature versus pressure level, $T(p)$ [upper plot]
- Example: Thermal Emission Spectrometer (TES) data for Mars (source NASA GSFC)
- Most engineering applications require density as a function of geometric altitude, $\rho(z)$
- Can use perfect gas law, $[p = \rho R T]$ and hydrostatic equation $[dp/dz = -\rho g]$ to get $\rho(z)$ from $T(p)$ [see separate handout]
- Can also use $T(p)$ in thermal wind equations to estimate wind [lower plot]

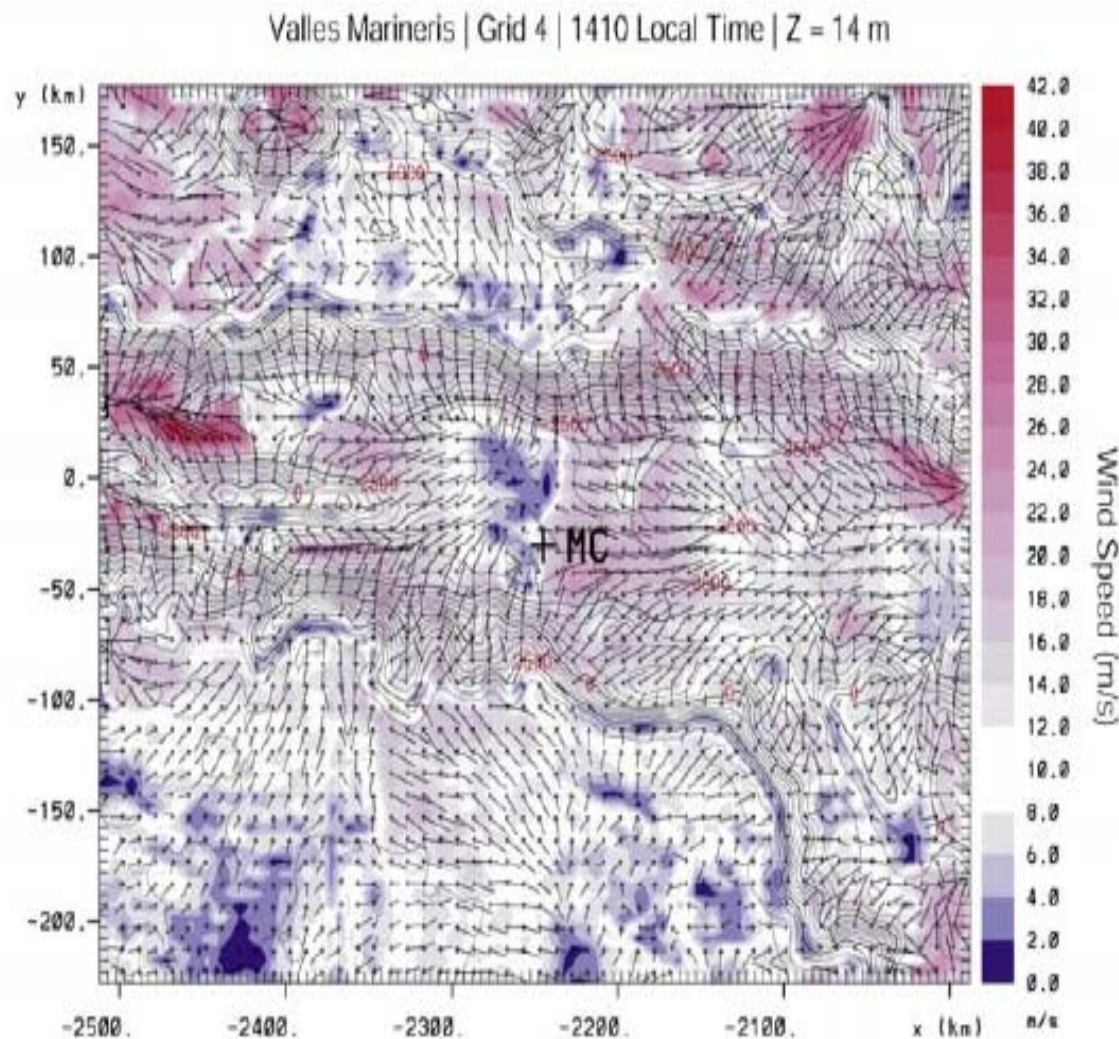
General Circulation Models (GCMs)



Cloud simulation with Mars GCM
Source: John Wilson, NOAA Geophysical
Fluid Dynamics Laboratory

- Global coverage, but at course resolution (typically a few degree lat-lon boxes and ~ 20-100 vertical levels)
- Solve equations of motion and energy balance (usually assuming hydrostatic equilibrium)
- “Sub-Grid Scale” perturbations are not simulated directly, but are parameterized as fluxes across grid-box boundaries
- Can provide short-term or long-term (climate) forecasts, as well as atmospheric diagnostics
- Can require long computer run times (~ several hours to days, depending on application and resolution)

Mesoscale Models



Local-to-regional coverage at moderately high resolution (grid boxes ~ few km on side)

Solve same equations of motion and energy as GCMs, but may assume non-hydrostatic

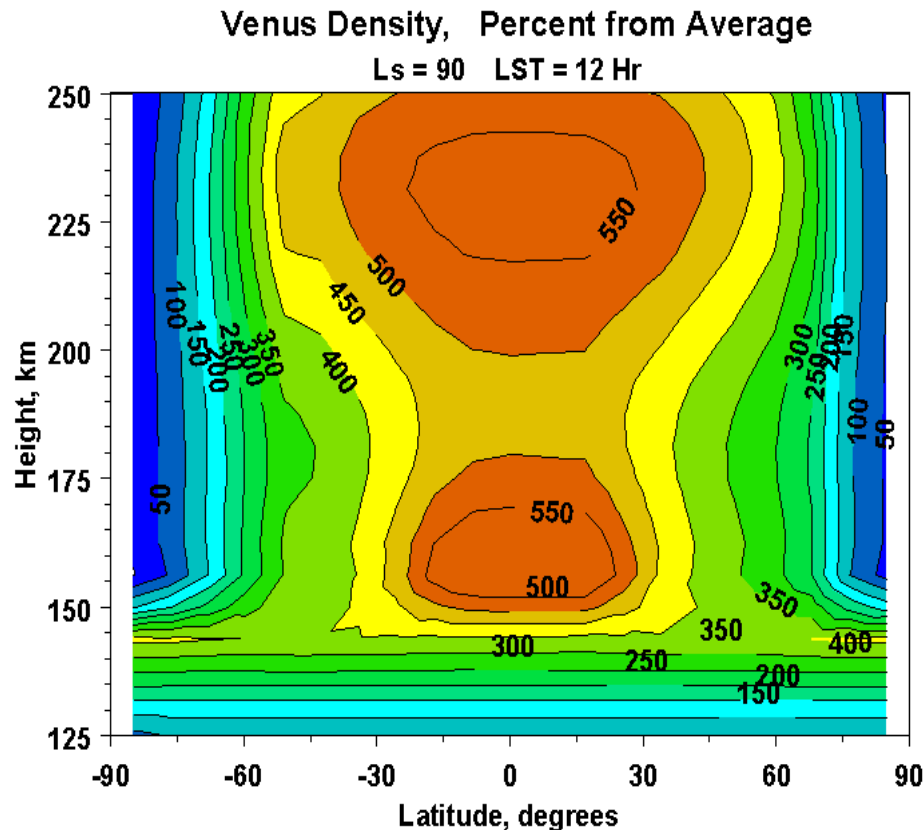
Sub-grid scale effects must still be parameterized

Good for atmospheric diagnostics and short-term forecasts

Can require very long computer run times (up to days, depending on application and resolution)

Mars wind simulation (MRAMS model)
Source: Scot Rafkin, SouthWest Research Institute

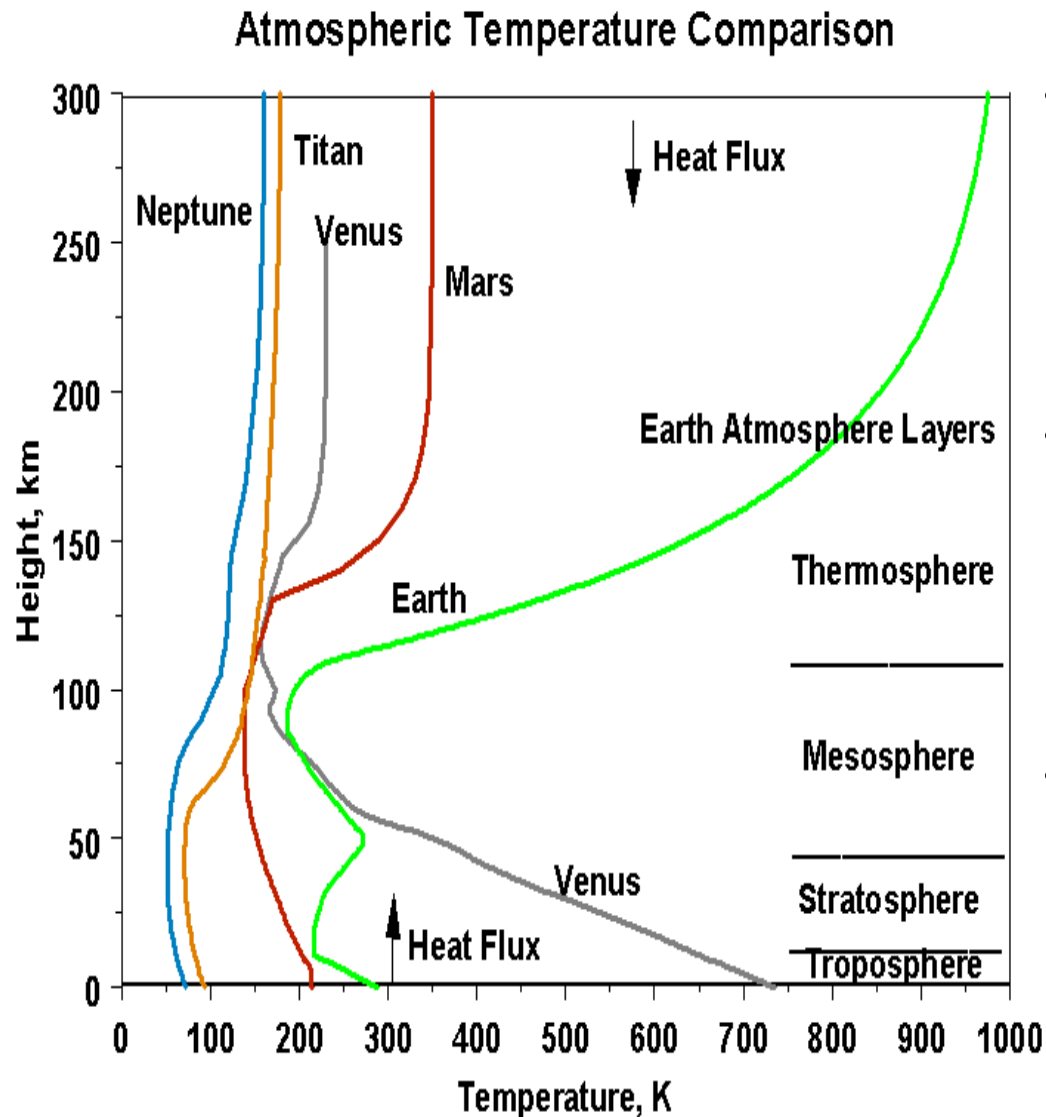
Engineering-Application Models



Source: Venus International Reference Atmosphere, as implemented in NASA MSFC Venus-GRAM

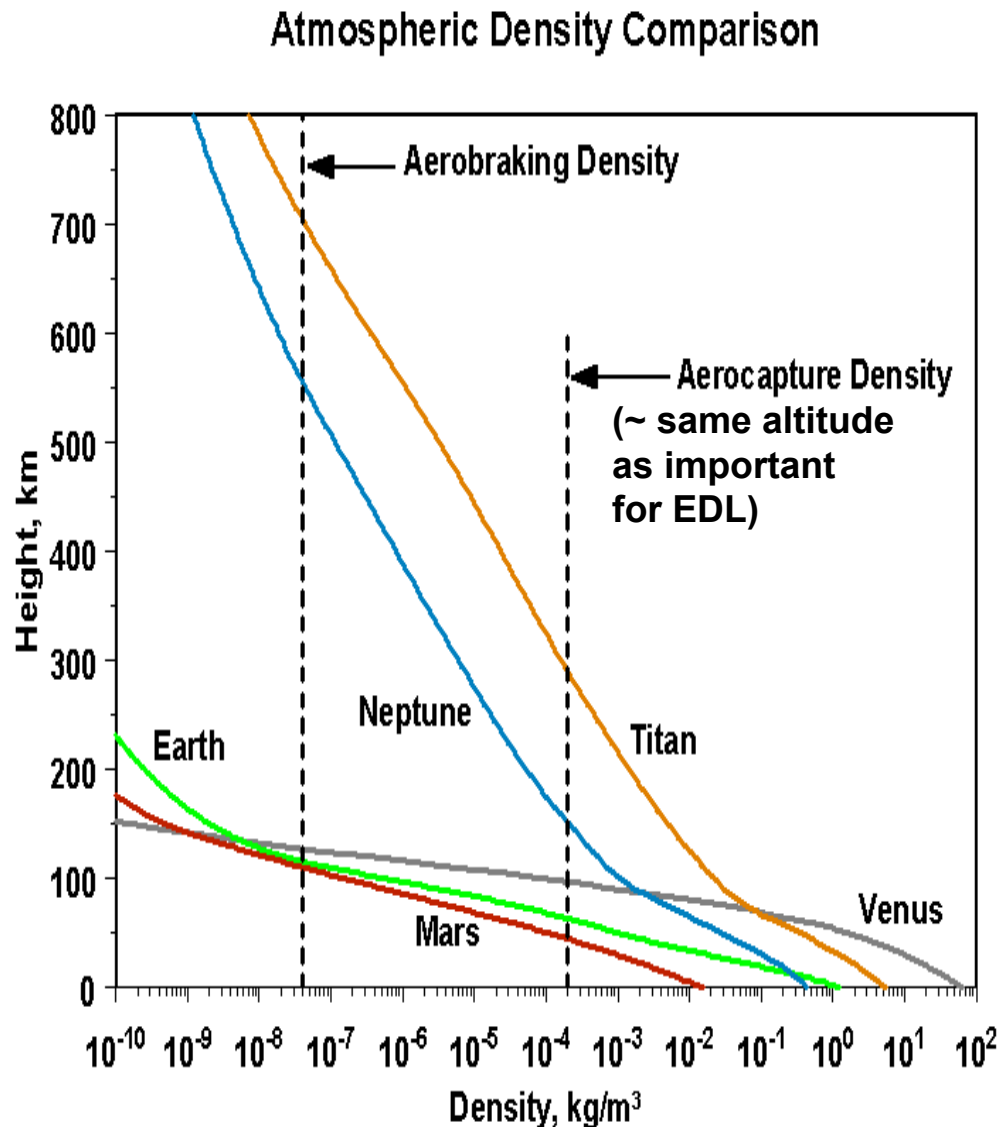
- NASA MSFC Global Reference Atmospheric Models (GRAMs)
 - Venus-GRAM
 - Earth-GRAM
 - Mars-GRAM
 - Titan-GRAM
 - Neptune-GRAM
- Use synthesis from measured global climatology and/or pre-computed output sets from science-application models
- Include perturbation model to statistically represent sub-grid scale atmospheric variability
- Models provide atmospheric diagnostics for temperature, density, winds, constituents, but do not provide forecasts

Atmospheric Temperature



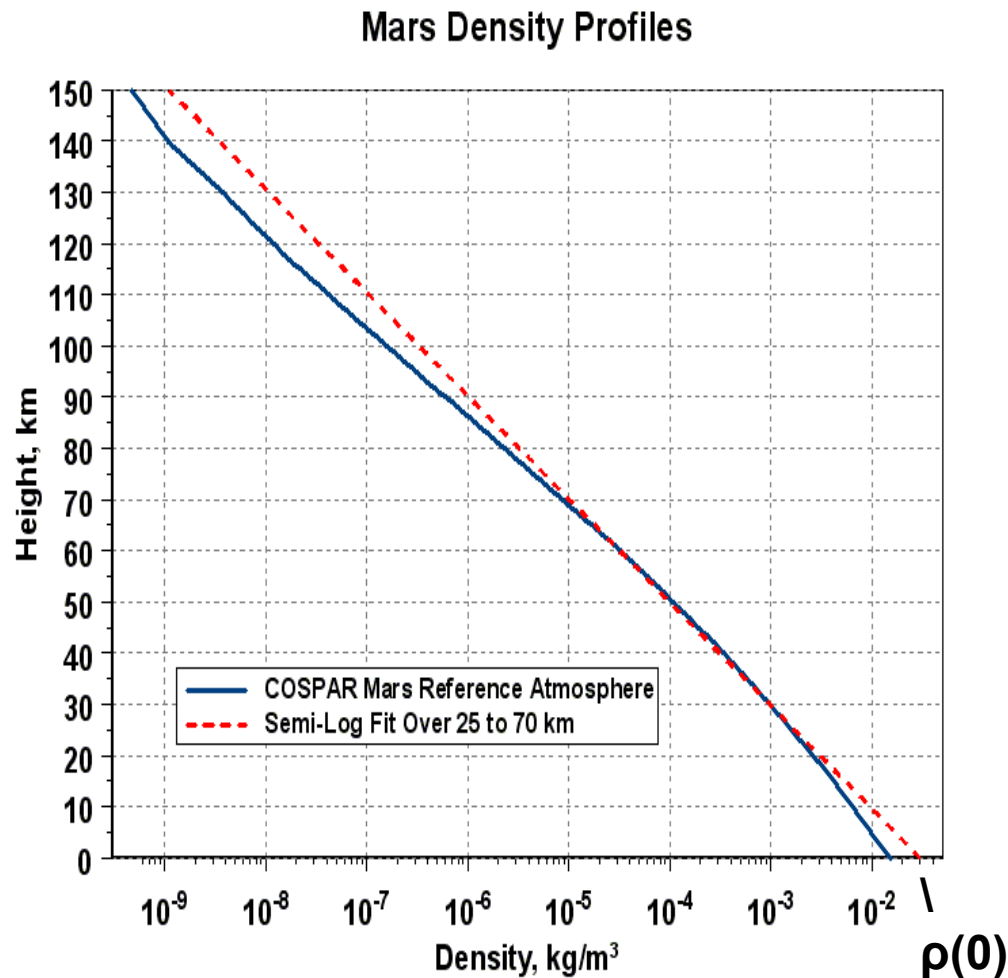
- All planets have decreasing temperature with decreasing altitude from the “top” of the atmosphere (downward flux of heat absorbed from UV and EUV Sunlight)
- Decreasing temperature with increasing height above surface (upward flux of heat from surface-absorbed sunlight, or from planetary interior)
- Earth’s unique temperature “bulge” in the middle atmosphere is due to absorption of UV by ozone

Atmospheric Density



- Density (ρ) determines spacecraft drag (D) and lift (L)
 - $D = C_D \rho V^2 A / 2$
 - $L = C_L \rho V^2 A / 2$
- Density always decreases with altitude
- Density decreases rapidly with height for terrestrial planets, but slowly with height on Titan and the gaseous planets
- Density “scale height” (H) measures rate of density decrease with altitude

Density Scale Height (H)



Definition:

$$H = - \rho / (dp/dz)$$

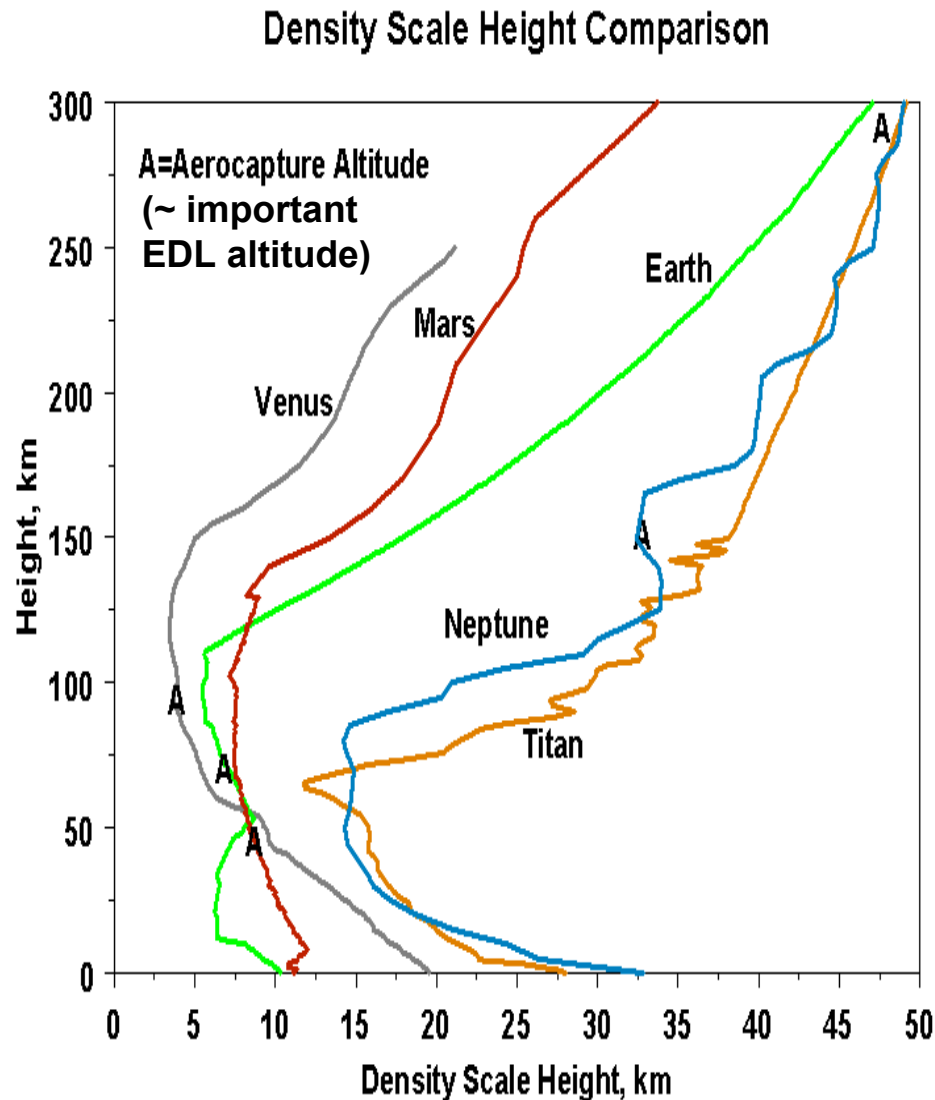
Calculation from 2 densities at 2 heights:

$$H = (z_2 - z_1) / \ln(\rho_1/\rho_2)$$

Exponential atmosphere if H is constant:

- $\rho(z) = \rho(0) \text{Exp}(-z/H)$
- Only works over limited height range
- Note: $\rho(0)$ is NOT same as surface density

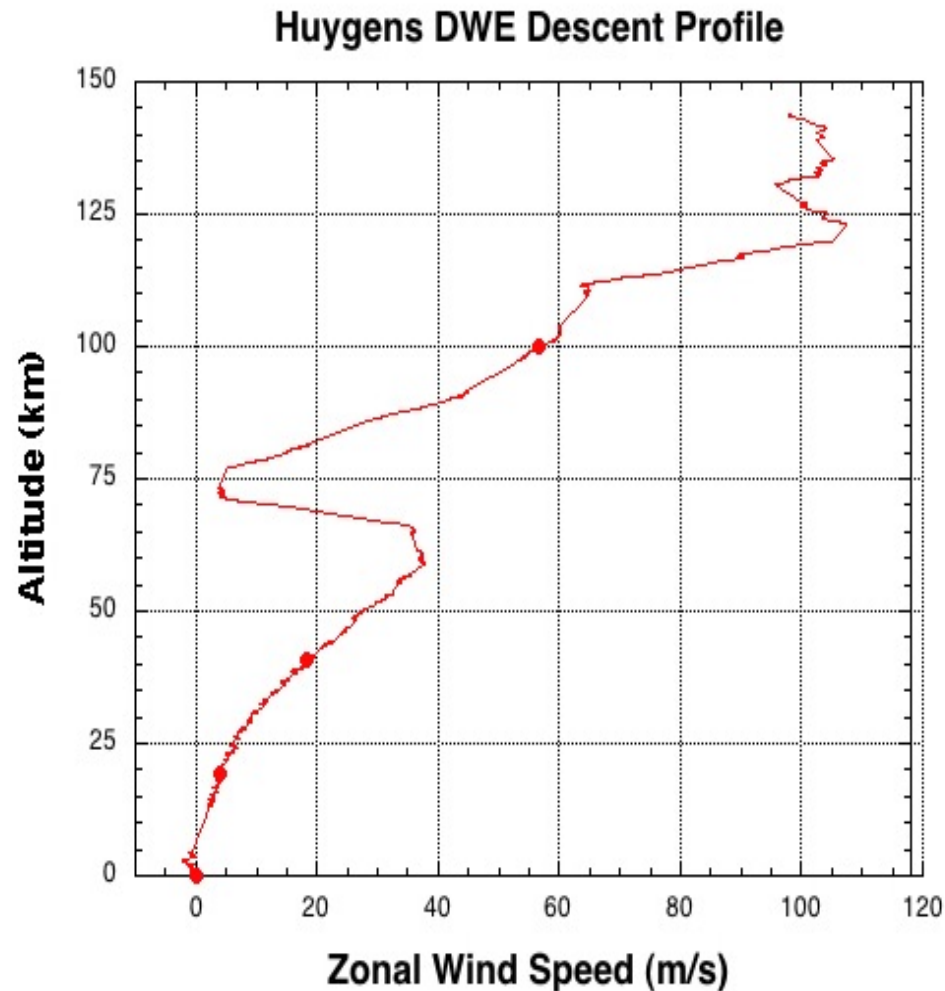
Density Scale Height: Important Factor for -



- Entry corridor width (range of usable flight path angles)
- Magnitude of maximum g-load (g_{max})
- Altitude, spacecraft velocity, and atmospheric density where g_{max} occurs
- Magnitude of maximum convective heat flux (q_{max})
- Altitude, spacecraft velocity, and atmospheric density where q_{max} occurs
- Magnitude of total heat load (Q_{tot})
- Sensitivity of g_{max} , q_{max} , and Q_{tot} to entry flight path angle

(See separate Handout)

Winds



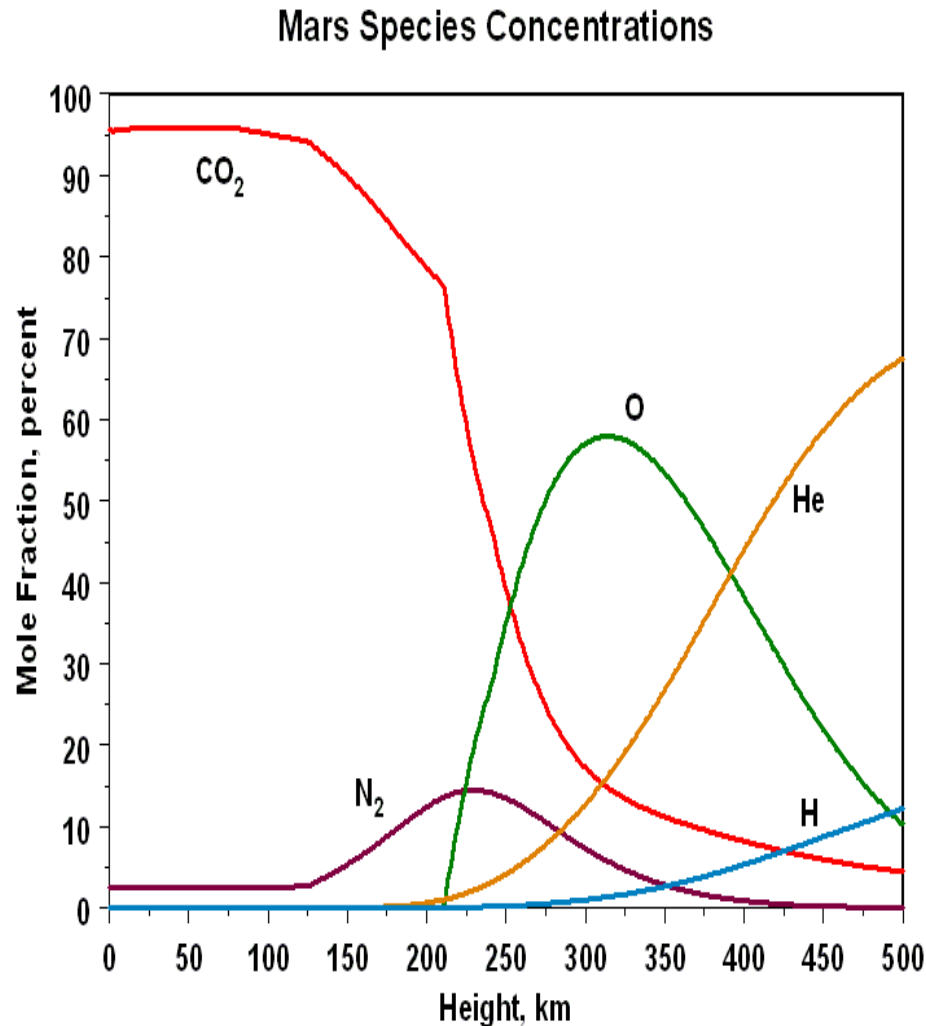
Not usually important at high altitude, with high (e.g. supersonic) spacecraft velocities

Can be important for parachute deploy and for spacecraft stability while on chute

Important for spacecraft drift while on chute (affects final landing footprint ellipse)

Titan winds measured during Huygens entry
Source: Planetary Data System

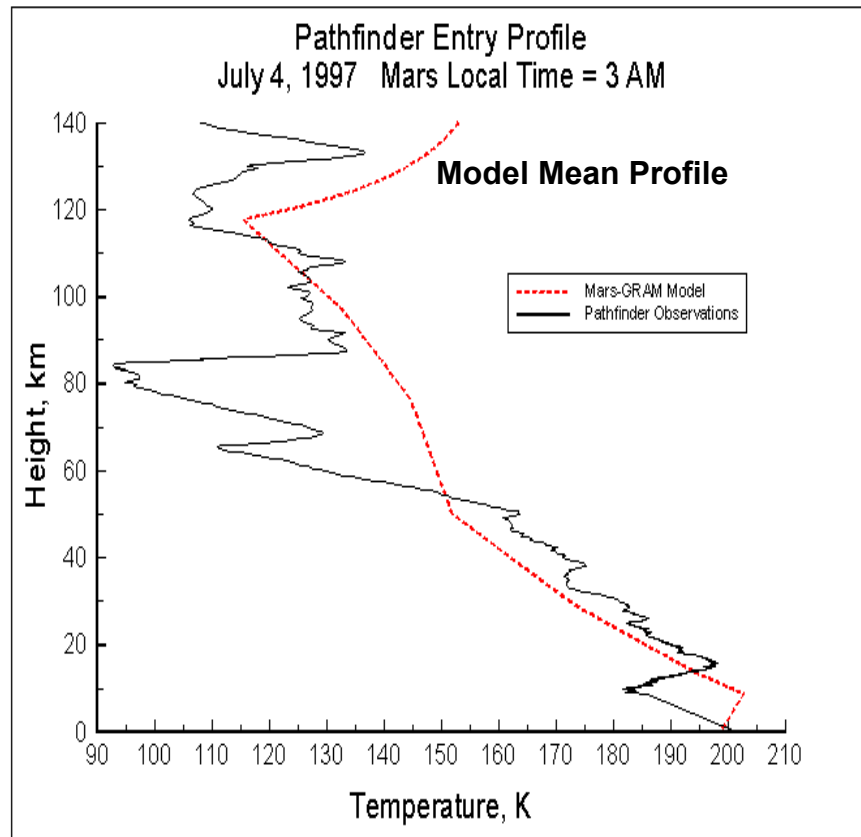
Atmospheric Constituents



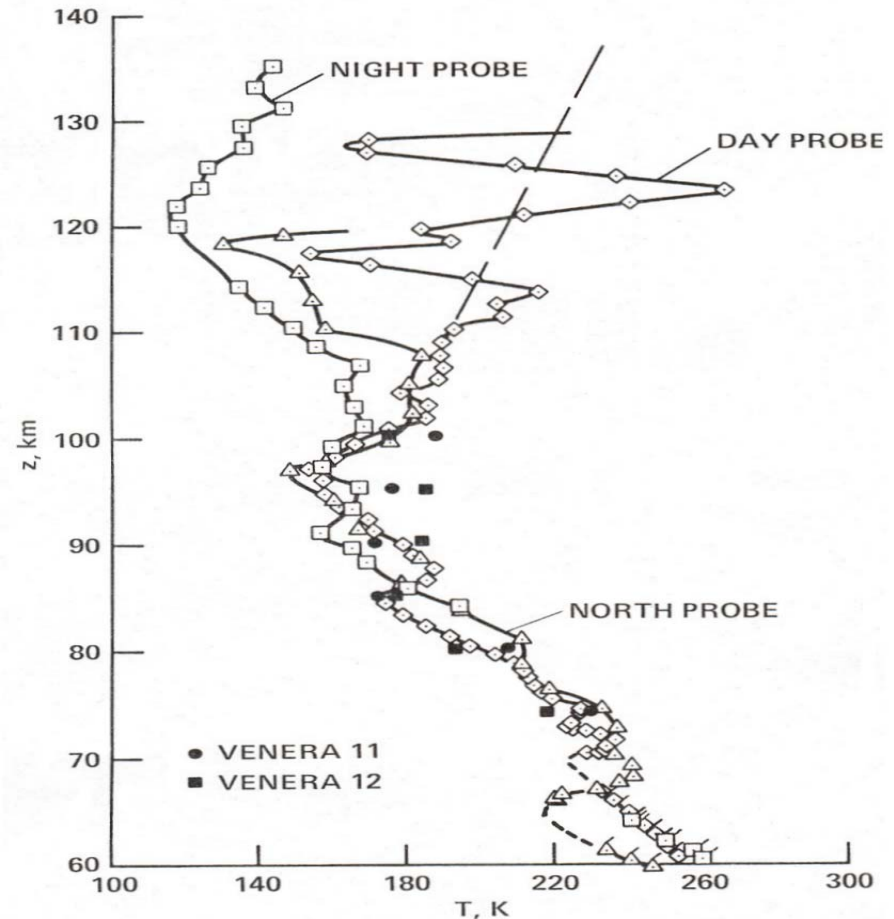
- Atmospheres are usually well-mixed below altitudes of interest for EDL
- Effects of natural constituents on EDL
 - Influence on mean molecular mass (M) in perfect gas-law relation, $p = \rho R_0 T / M$, hence affecting density (ρ) and density scale height (H)
 - Influence on convective (and radiative) heat flux coefficient
- Induced constituents can be important for radiative heating
 - Example: production of CN radical (from N₂ and CH₄) by high entry temperatures produced during EDL into Titan's atmosphere
 - CN radiates strongly in UV, causing significant added radiative heat flux and heat load (above convective values)

Atmospheric Perturbations

All observed atmospheres have significant “high frequency” perturbations of density and winds, as well as large-scale (e.g. global, seasonal, and time-of-day) variations

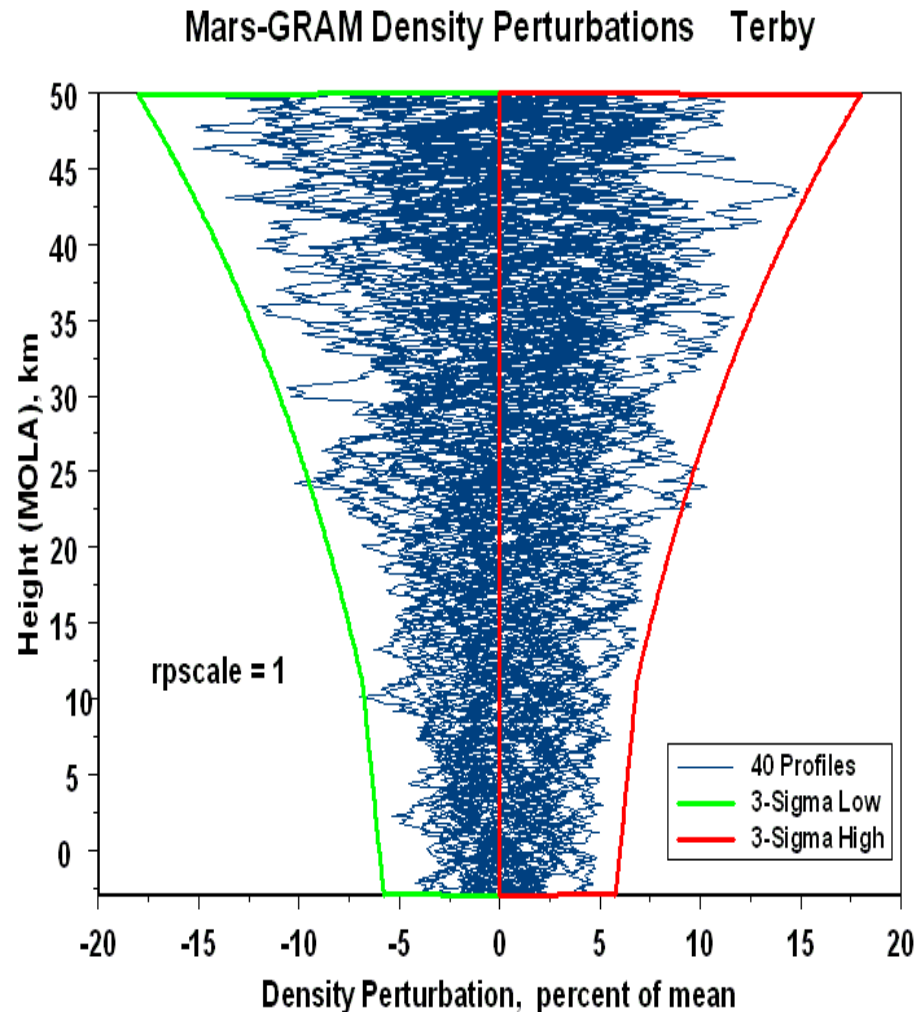


Mars (Pathfinder)



Venus (Pioneer and Venera)

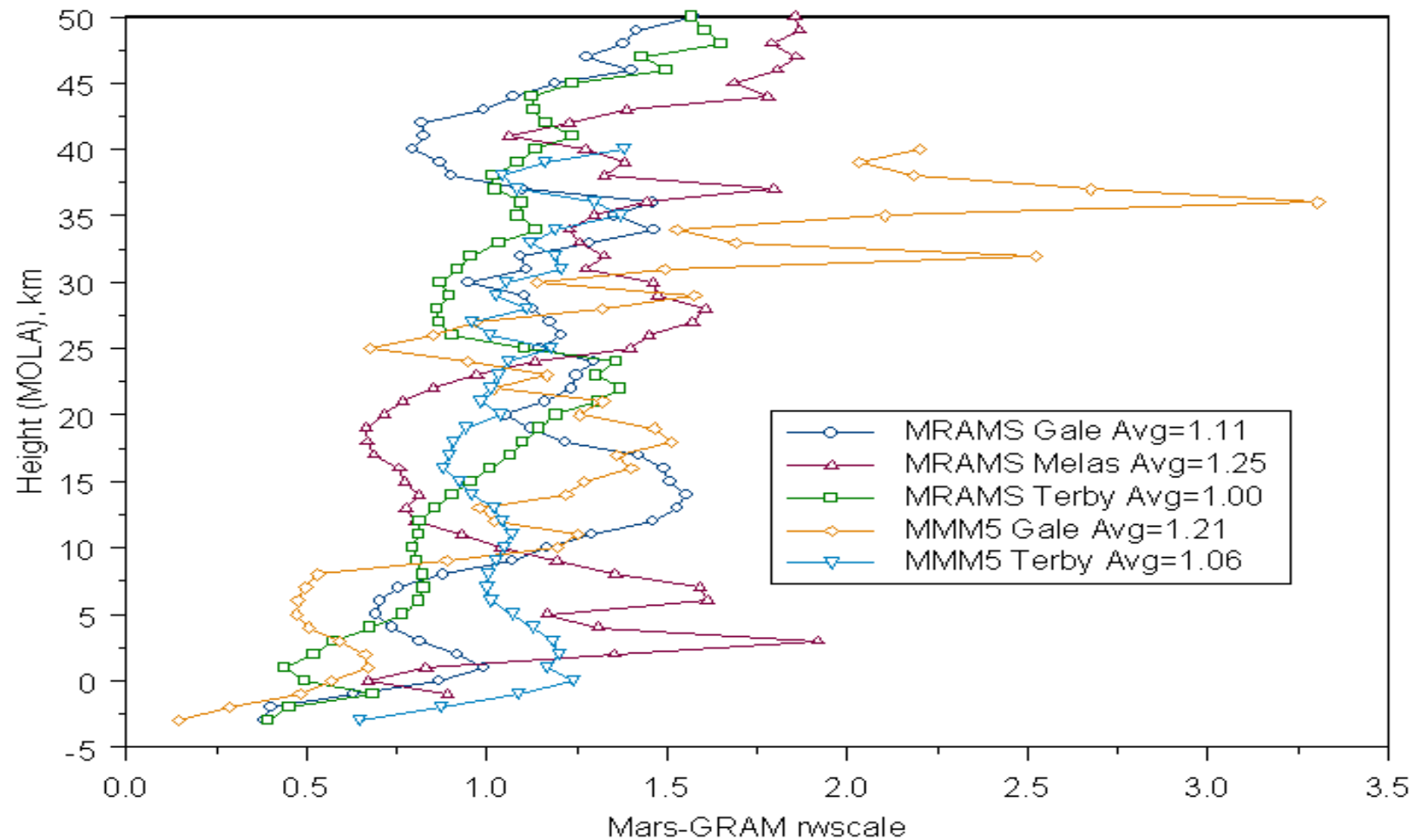
Perturbation Simulations



Mars-GRAM-simulated “high frequency” density perturbations

- NASA MSFC GRAMs simulate both large-scale variations and “high frequency” perturbations
- Perturbation Effects are Important for –
 - Thermal Protection System (TPS) performance (mostly large-scale variations)
 - Stability of spacecraft attitude
 - Landing footprint dispersion size
 - Guidance, Navigation, and Control (GN&C) algorithm design
 - GN&C system hardware performance
- Density perturbations more important at high altitudes (high speeds); winds generally more important at low altitudes

Validation of Mars-GRAM Wind Perturbations



- **MRAMS** mesoscale model output courtesy **Scot Rafkin** (SouthWest Research Institute)
- **rwscale** = ratio of wind standard deviations (MRAMS/Mars-GRAM)
- **Gale, Melas, Terby** = Three Mars Science Laboratory candidate landing sites

Additional Information in Handout

- **A handout, provided separately, gives details on:**
 - Equations for “back-of-the-envelope” calculations of max g-load (g_{\max}), max convective heat flux at the stagnation point (q_{\max}), and total convective heat load (Q_{tot})
 - Selected environmental parameter values for several planets and Titan
 - References for methods and data
- **The handout covers only low L/D EDL**
- **Effects of high L/D (not addressed here) include:**
 - Significantly reduces g_{\max}
 - Lowers q_{\max}
 - Raises the altitudes (and lowers the densities) at which g_{\max} and q_{\max} occur
 - Increases Q_{tot}